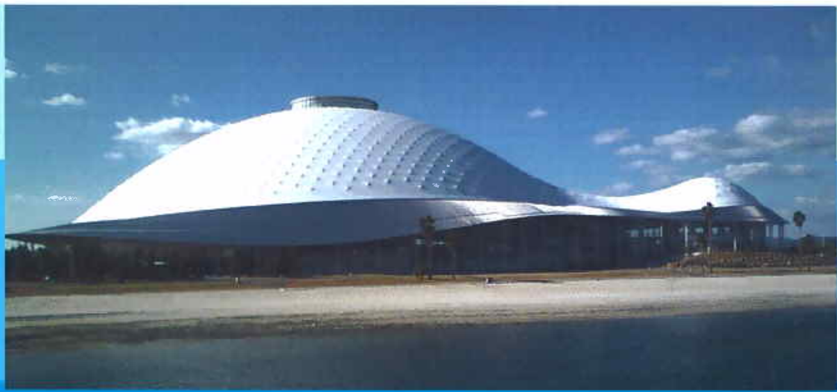
JOURNAL OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES

FORMERLY BULLETIN OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES

Prof. D. h-C Eng .E. TORROJA, founder



Vol. 53 (2012) No. 2

June n. 172

ISSN: 1028-365X

Journal

VOL. 53 (2012) No. 2
n. 172 June

contents

Memorial Statement

Retrospectives on Concrete Shells

Technical Papers

COVER: *Figure from paper by T. Takeuchi, S.D. Xue, S. Nakazawa and S. Kato*

IASS Secretariat: CEDEX-Laboratorio Central de Estructuras y Materiales
Alfonso XII, 3; 28014 Madrid, Spain
Tel: 34 91 3357409; Fax: 34 91 3357422; iass@cedex.es; http://www.iass-structures.org

Printed by SODEGRAF ISSN:1028-365X Depósito legal: M. 1444-1960

STATE-OF-THE-ART OF SEISMIC RESPONSE EVALUATION METHODS FOR METAL ROOF SPATIAL STRUCTURES

Shoji NAKAZAWA[1], Shiro KATO[2], Toru TAKEUCHI[3], Su-Duo XUE[4], Carlos LAZARO[5]

[1] Associate Prof., Dept. of Arch. and Civil Eng., Toyohashi University of Technology, Toyohashi, Japan
[2*] Prof. Emeritus, Toyohashi University of Technology, Toyohashi, Japan
[3] Prof., Dept. of Architecture and Building Engineering, Tokyo Institute of Technology, Tokyo, Japan
[4] Prof., College of Arch. And Civil Eng., Beijing University of Technology, Beijing 100022, China
[5] Prof., Dept. of Continuum Mechanics and Theory of Structures, Universidad Politecnica de Valencia, Spain

Editor's Note: Manuscript submitted 16 October 2011; revision received 18 May 2012; accepted 1 June. This paper is a version of a chapter for a State-of–the-Art Report on seismic response of metal roof spatial structures by IASS Working Group 8: Metal Spatial Structures. The paper is open for discussion and comment, which may be sent both to the Editor of the Journal and to the chair of Working Group 8 (S Kato, kato-shiro@tg.commufa.jp).

ABSTRACT

The present paper is a result of a collaboration in IASS WG 8 for metal spatial structures to prepare state-of-the-art reviews for earthquake response analysis methods and equivalent static seismic loads for metal spatial structures. It quotes mainly investigations from IASS symposia and related journals. First, the dynamic response characteristics of metal spatial structures are briefly explained. This is followed by a review of analytical methods for evaluating earthquake responses. Finally the equivalent seismic loads proposed for metal spatial structures are reviewed and some comments for future analysis of failure and fragility are provided.

Keywords: *Metal Spatial Structures, Seismic Response Evaluation, Equivalent Static Seismic Load, Risk Analysis*

1. INTRODUCTION

Metal spatial structures cover effectively large areas without columns inside, and they have been applied to many kinds of roof structures for various purposes. Their geometries range from flat plates to curved ones such as arches, cylinders, spheres and free forms in some special cases. The response characteristics to earthquakes also vary depending on their geometries and supporting structures, and accordingly, several reviews [1-6] and guidelines [7,8] quoting many studies have been published depending on the geometries and considering the substructures of the spatial structures.

In general, flat roofs are apt to be subjected to up-and-down vibration due to UD components of earthquake motions [9]. On the other hand, roofs with some rise, for example, cylindrical lattice roofs and lattice domes are subjected to large asymmetric vertical accelerations even under horizontal earthquake motions [10, 11], and their responses are determined and much influenced by several asymmetric modes with non-zero participation factors. And because of their difference of responses from tall buildings, such roofs have a large number of parallel vibration modes and roof-substructure coupling appears if supported by a substructure. Since equivalent static seismic forces are not specified, design codes with a focus on spatial structures, evaluation of responses and seismic loads to roof spatial structures are required in their structural design. Also, in case of very wide structures, earthquake motions will be different from one support to another, raising up the effects of wave passage or irregular soil conditions.

The lessons [12-15] from earthquake damages, such as Kobe Earthquake of 1995 and Great East Japan Earthquake 2011 in Japan, tells us clearly a fact that, although several structures were damaged partly, many spatial structures themselves could survive earthquakes but were damaged as found in many patterns: flake-off of concrete at shoes, rupture of anchor bolts, rupture of braces and members around shoes due to tension just after buckling, and falling-down of ceilings and equipments attached on ceilings. Damage to ceilings has given rise to loss of functions as buildings. The same typical failure patterns were reported [16, 17] with respect to the damages of grid structures by Wenchuan Earthquake of 2008 in China. And soon after Kobe Earthquake, engineers have deeply understood that applications of base isolation system [18-24], hysteresis damper system [25-28], and viscous or viscous-elastic damper system [29-31] work effectively and they have intensively studied for the metal spatial structures. Recently, several damping devices have been introduced into realized metal spatial structures as reviewed in the references [3, 20, 21, 32-33]. Accordingly, seismic response evaluation methods for metal spatial structures implemented with isolation and damper systems are also required in the structural design. And it is necessary to investigate and propose an efficient evaluation method for seismic performance in consideration of the damages to not only major structural members but also non-structural components.

The present paper focuses on methods for evaluating responses and seismic loads to metal roof spatial structures with plate or shell-like geometries. Papers mainly in IASS Proceedings, IASS Journals and similar engineering journals are to be reviewed and referred. First, dynamic response characteristics are briefly explained, then followed by review of analytical methods for evaluating earthquake responses and equivalent seismic loads, and complemented by some additions for evaluating structural performance. The design earthquake motions, earthquake response analysis methods, application of energy absorbing dampers, evaluation of structural performance and other related researches are to be reviewed in detail in the forthcoming state-of-the-art reviews and accordingly they are briefly commented in the present paper.

2. GEOMETRY AND SUPPORT CONDITIONS FOR METAL ROOF SPATIAL STRUCTURES

2.1 Geometry and member arrangement

The present paper puts a focus mainly on metal roof spatial structures with two or three-dimensional spread. The geometries are classified as many types from flat plate-like structures to shell-like geometries such as arches, cylinders, spheres and free forms in some special cases. Examples are found and discussed in the references [1-9] and Chinese code for metal spatial structures [34].

Metal spatial structures are in most cases formed using bar elements with both axial and bending rigidities. In case of shell-like configurations, bars are arranged in two or three directions forming shell surfaces. In some cases, surface elements, not so many, are applied for fulfilling their structural requirements. Several interesting cases are given in the references [7, 8, 35, 36] for bar elements.

2.2 Supporting structures

Supports for metal roof structures are fundamentally classified as follows; one is a direct support by firm foundations at ground level (named here as boundary condition DF-R), and the other is a support where a substructure is constructed using walls or columns for supporting roofs of superstructures (named as boundary condition SUB-R). In a special case of direct but flexible foundations or extremely wide structures, earthquake motions will be different from one support to another. This case needs a caution to the effects of wave passage or irregular soil conditions, asking structural engineers to do a more elaborate dynamic analysis.

In case of boundary condition DF-R, a rigid fundamental boundary is a pin support at all boundaries of a rectangle or a circular plan. System of simple support is often adopted in case of rectangular plan, which has been also encountered in mathematical analysis of continuum shells. In case of roofs with free edges, boundaries are usually stiffened by edge beams and/or vertical columns to transfer loads to several rigid supports on the foundations on the ground, where the stiffening edge beams provide membrane action and suppress deformations and bending moments.

In case of boundary condition SUB-R, several different supports are considered. One of possible cases is a roof structure which rests on a platform supported by columns or braces. The boundary may be a rectangular plan or a circular plan. In design, a substructure is often realized as one story or low multi-stories. Some structures are supported by substructures implemented by ductile braces with high energy absorption or viscous dampers.

3. RESPONSE CHARACTERISTICS AND DAMPING PROPERTIES

3.1 Earthquake motions and design spectra

Earthquake motions act to roof structures horizontally and vertically at foundation level. In most cases, earthquake motions are assumed in design to act uniformly in the horizontal or vertical directions, and such motions are often applied as accelerations from rigid foundation. The earthquake intensities may be varied depending on different construction sites in each country, and usually engineers adopt design response spectra according to some design codes for determining the intensities at construction sites [34, 37-39]. Some codes may adopt one level of intensity for seismic design, and some codes adopt multi-intensity levels depending on their assumed limit levels: one for serviceability limit level and one for ultimate limit level.

Most design codes consider only horizontal earthquake motions for design use. However, vertical components will be required when they seem to give much effect to structural responses or simultaneous actions with the horizontal components seem important. Such examples which considered the vertical earthquake components are found in reference [40].

3.2 Horizontal and vertical responses

In general, vertical responses appear when roof structures are subjected to vertical earthquake motions, and horizontal responses when subjected to horizontal earthquake motions. In most cases, horizontal input components are much lager than the vertical input components [40]. However, the effects of vertical components will be important for horizontally large roofs in some cases that the site of buildings are very near from epicentre area. Several researches [9, 41] have found that the vertical responses of roofs are dependent on not only support conditions by substructures or direct foundations but also their geometries.

Comparing with tall buildings, several different features are found in the dynamic behavior of metal roof spatial structures, although common similarities exist as dynamic responses to earthquakes vary depending on not only the material of structural members, material damping but also boundary conditions. As characteristically found in the responses of arch-like roofs, they are subjected to large anti-symmetric vertical deformations even under horizontal earthquake motions [7, 8, 10, 11]. The main reason for their response characteristics is nested in the shell-like geometry with some rise over a large domain, and it is known as a mechanism that such roofs have a large number of parallel adjacent vibration modes with anti-symmetric vertical components. The anti-symmetric components are stimulated simultaneously due to horizontal earthquake motions, and their amplitudes change drastically dependent on dynamic coupling between roofs and substructures [42, 43].

3.3 Effects of wave passage effects and irregular soil conditions

Usually, foundations are assumed as rigid, and in such a case earthquake motions are applied uniformly as accelerations at the foundation level. However, if the foundations are flexible and occupy a large area under roofs, the earthquake motions will be different from support to support due to seismic passage effects or time delay of arrival. Similar different input earthquake motions at support to support happen in case of irregular soil strata within a construction site. Several researches [44-48] are found with respect to the effects of wave passage and irregular soil strata. In the analysis, not only acceleration but also velocity and displacement are required as inputs for analysis.

3.4 Damping properties

Responses are strongly influenced by the magnitude of damping of structures. The damping is concerned with structural material, connection types (weld or mechanical fasteners), soil-structure interaction, radiation damping, and in some cases of light structures, finishing materials for roofs and ceilings. Conventionally for steel roof structures, a damping factor around 1% to 2% is often applied, and approximations are adopted for damping as Rayleigh damping or stiffness proportional damping. In general, a spatial structure is structurally divided into several parts. In case that material of a superstructure differs from that of a substructure, for example, a steel lattice roof is supported by a RC substructure, a combination of Rayleigh damping and stiffness proportional damping is applied [49, 50]. Because of large damping effects to responses and also due to some ambiguity, such a conservative approximation for adopting relatively low damping factors has been applied in design calculation. Measurements [51] have still been continued to find the values of damping factors, and a database [52] of the damping factors is being piled up gradually.

As a more prominent trend in recent years, artificial damping devices [3, 4] have been introduced to reduce responses; viscous dampers [31], visco-elastic dampers [29], hysteresis dampers as buckling restrained braces [53], and more actively base isolation [20, 21] with energy absorbing dampers. Also some developments of devices [23, 24, 27] are found as researches to evaluate the effectiveness [18, 19, 22, 25, 26] of such devices. Usually we expect a large amount of response reduction when applying these kinds of devices. In time history response analysis, such damping devices are modeled considerably in detail as much as possible. On the other hand, when using modal analysis, the concept of equivalent stiffness and equivalent viscous damping is applied in approximation for nonlinear responses [26, 43, 55].

The above described characteristics, being different from ordinary tall buildings, require engineers to evaluate earthquake responses and seismic loads for structural design, since there are few available design codes for this kind of seismic loads and also since engineers are asked to investigate more accurately the effectiveness of artificial devices when applied to realization.

4. ANALYTICAL METHODS FOR EVALUATING EARTHQUAKE RESPONSE

The publications from AIJ [7, 8] and the Specification [34] provide design procedures for metal spatial structures for not only buckling but also earthquake resistant design. And the publication from AIJ [38] provides a general procedure to evaluate seismic loads considering several limit states.

The seismic intensity for design is given in general as a base shear coefficient of a certain value for static analysis in which a distribution of seismic loads is prescribed depending on a building height. Even in case that seismic design loads are given as a design spectrum for acceleration response, as similarly to the codes [37, 38], in most cases, there are no descriptions or comments for seismic loads for roof spatial structures in the U-D direction vertical to the roofs. As already described, spatial structures with some rise are apt to be subjected to relatively large U-D seismic responses even under horizontal earthquake motions, and engineers are asked to evaluate the distribution within a horizontally wide roof for displacements, forces in members, and other necessary quantities based on dynamic response analysis.

In case of linear responses, the evaluation of responses is mainly based on CQC (Complete Quadratic Combination) method or SRSS (Square Root Sum of Squared) method. On the other hand, if the structures are designed allowing and based on elasto-plastic response, direct time history analyses are often performed. In principle, in need of time history analysis, such design spectrum is interpreted as time series of accelerations. Accordingly, there might be more than two paths for practical design as illustrated in Fig.1 [1].

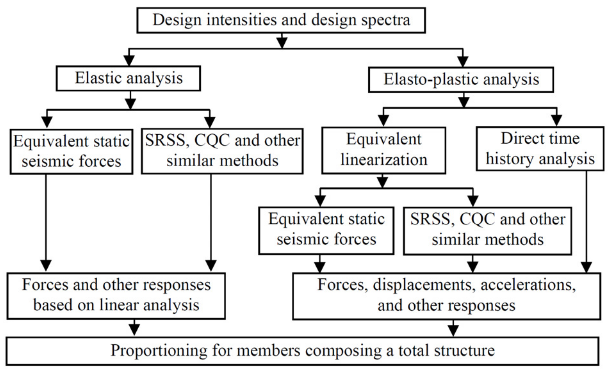


Figure 1. *Design flow for member proportioning [1]*

Nowadays many efficient analytical methods compiled as computer software can be applied as often encountered in practice, and whichever static or dynamic, elastic or plastic analysis is adopted from (1) modal analysis, (2) pushover analysis, and (3) time history analysis, engineers are required to establish an accurate structural model for the structure in issue to be capably analyzed using analysis computer software, under a comprehensive consideration of substructures, foundations, and damping devices if any special devices for vibration control are introduced.

4.1 Modal analysis and CQC method

Modal response analysis is simple and cost-effective compared with time history analysis. As such analyses, SRSS and CQC methods are often applied in practice. CQC is adopted in several recommendations, for example, in the references [34, 38]. In case of presence of closeness in frequencies between several modes, CQC has been applied, for example, in the studies for lattice domes [11] supported by substructures. Even in the case that an investigation for elasto-plastic behavior is required to include the effects of base isolation, elasto-plastic dampers and viscous dampers, such SRSS and CQC have been applied together with use of equivalent linearization of elasto-plastic behavior [26, 51, 55]. In the study of single layer lattice domes supported by buckling restrained braces with a ductile hysteresis [26], comparison was shown fine between the modal analysis based on equivalent linearization and the direct time history analysis. Based on the studies [57, 58], equivalent static seismic loads have been also proposed as practical and approximate loads for static analysis.

4.2 Random vibration analysis

Random vibration analysis method is considered as a reasonable means for analyzing the stochastic responses of structures, since earthquakes are considered one of random processes. For the analysis, input power spectral density (PSD) matrix, output PSD matrix and frequency response function matrix are indispensable. However, when structures have too many degrees of freedom, or especially when the structure is subjected to multiple ground excitations, the computational effort would be quite large. To promote the application of random vibration method to practical seismic design, Xue et al. [59, 60] not only studied a seismic random model based on the new Chinese seismic design code (GB50011-2001) but also further improved and developed the method for seismic analysis of spatial structures to investigate the random responses of spatial structures. In the studies multi-component seismic excitations are evaluated by introducing the concept of Pseudo Excitation Method (PEM). In the review paper [2] for dynamic analysis of spatial structures, researches on random vibration analysis are also referred.

4.3 Pushover analysis

Pushover analysis is sometimes applied as performance based design to tall buildings, for example, as shown in the reference [39]. In this scheme based on static nonlinear analysis, an equivalent static seismic load is utilized in an elasto-plastic analysis to confirm that the total structural capacity satisfies several given limit states, under an assumption that equivalent stiffness and equivalent damping ratios can be accurately evaluated depending on a stress-strain relationship in each structural member. With respect to metal roof spatial structures, very few studies for performance based design are found except for the references for lattice domes. The studies [43, 61, 62] have proposed equivalent static seismic loads for domes supported by buckling restrained braces of stable bi-linear hysteresis [43], while supported by braces of deteriorated hysteresis under buckling [61]. In the study [62] for metal spatial structures being covered with membrane roofs and globally supported by a reinforced concrete substructure, an adaptive scheme for equivalent static seismic loads has been proposed for a pushover analysis, considering the change of modes depending on deformations.

4.4 Direct time history analysis

In case that equivalent static seismic loads are not proposed in any recommendations or a more detailed analysis is required in need of design purpose, a set of time history analysis are performed to find earthquake responses using direct time history accelerations. Also in need of multi-input earthquakes, time history analysis is performed using accelerations together with velocities and displacements as their inputs. In these occasions, whichever the analysis is elastic or elasto-plastic, a structural model of the total structure is constructed considering mass and stiffness-strength distributions.

In the design procedure for ultimate limit level, engineers are asked to perform nonlinear response analysis considering large deformation and plasticity of material. In this case, the analysis becomes time-consuming since material and geometrical nonlinearities are needed at each time step in analyses.

Recently, roof spatial structures with energy absorbing devices such as buckling restrained braces in their substructure or an intermediate base-isolation system have been proposed for reducing the responses. Artificial and added damping devices are well known effective, and not only hysteresis but also viscous dampers are nowadays being adopted in many projects [18-24, 26-33, 49, 51]. Since an earthquake input to an upper roof structure from its substructure is reduced greatly with use of seismic control devices, the roof structure may remain in an elastic range. Accordingly, modal analysis such as the CQC method may be adopted as a prediction method of the maximum responses, once such seismic devices be modeled as equivalent stiffness and damping. However, for spatial structures with seismic control devices, seismic resistance capacity and collapse accelerations are usually evaluated based on time history elasto-plastic dynamic analysis. In reference [25], a lattice dome of 100m span supported by ductile braces was also investigated. The investigation reported an imortant design suggestion that, if domes are designed resisting two time the self weight, the failure will not be probable and that the failure accelerations will be beyond 500cm/s^2 for domes if an ordinary yield base shear coefficients of 0.2 to 0.4 for braces is adopted for its substructure.

5. EQUIVALENT STATIC SEISMIC LOADS

When equivalent static seismic loads are available for design corresponding to given geometries and structural properties, they can be applied cost-effectively. The specifications or recommendations [34, 38] give a procedure to evaluate the elastic stresses under its design earthquake. The procedures based on CQC method can give elastic stresses for members in a fine accuracy; however equivalent static seismic loads as vectors, which can be applied to static analysis as loads, have not been provided yet. In the followings several examples are reviewed for equivalent static seismic loads including the effects of anti-symmetrically vertical components.

5.1 Statically equivalent seismic loads based on time history analysis

In general, a fact that several modes are excited in roof structures burdens difficulties in estimating statically equivalent seismic loads based on a single predominant mode. In actual structural design for several cases explained in the references [7, 8], the static seismic loads of complicated spatial structures have been determined for practical use based on time history response analysis. In other words, the distribution and intensity over a roof as statically equivalent seismic loads are decided by an assumption that the maximum seismic loads occur at the same time when some important design value in the domes becomes maximum. The important values might be a total base shear, total strain energy, axial forces in important members, reaction forces at important supports, specific displacements or accelerations at some important points, or others depending on its importance in the design. Single layer reticular domes both for high rise and low rise were studied in the study [10], where static seismic loads for single layer domes are estimated based on time history analysis.

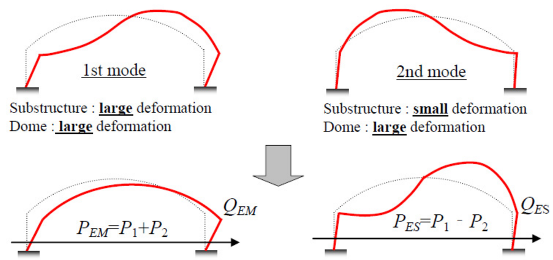
5.2 Equivalent static seismic loads based on modal analysis and application to pushover analysis

(a) Modal analysis

Single layer reticular domes with 100m span supported by braces of substructure were studied [26] considering several parameters such as depth-to-span ratio (d/L). The response characteristics of domes with five different depth-to-span ratios were analyzed by paying attention to the number of the exciting vibration modes. Based on the study, a method has been proposed to estimate the earthquake loads to a dome structure supported by a substructure using a concept of equivalent linearization. The results are compared with those of nonlinear responses analysis, giving a fine agreement between them, however under a restriction that the nonlinearity is caused only in braces at substructure level. In the case of a dome with small d/L, many modes contribute to the maximum response of the dome. On the other hand, in case of a dome with relatively large d/L, only two dominant modes contribute greatly to the response, and it is confirmed that the distribution of maximum response acceleration can be estimated only using two dominant modes.

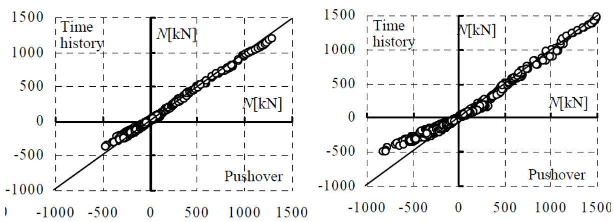
(b) Two-mode based expression for equivalent static seismic loads

Considering a single layer lattice dome of 100m span, supported by substructures consisting of braces with stable bi-linear hysteresis loops, a set of equivalent static seismic loads have been proposed using two dominant modes [58], however under a condition that the sum of equivalent total mass ratios is larger than 0.9 for the two dominant modes. One is a load corresponding to the dominant sway mode, while the other to the dominant anti-symmetric mode. The scheme can be applied in both cases for elastic and elasto-plastic behavior since the evaluating scheme is based on equivalent linearization method. However, its application will be limited to domes with a ratio of member diameter-to-span being greater than 1/100. The method is extended into double layer lattice domes of 100m span [43], considering the braces experiencing plasticity under severe earthquake motions, and it is proved efficient in the case that the total mass ratio for the two dominant modes are lager than 90%. In the case of braces experiencing deteriorations under buckling, a study [61] was also presented, by replacing the deteriorated hysteresis into equivalent stable bi-linear ones, to estimate a set of equivalent static seismic loads in vectors. The proposed static seismic loads [43, 58, 61] are compared with those obtained based on time history nonlinear analysis, leading a result that the forces from the static seismic forces give almost same and safe side values as those from direct time history analyses. Figure 2 shows a set of seismic loads estimated by two dominant modes, and Figure 3 illustrates the comparison of axial forces due to horizontal seismic motions between pushover analysis and time history analysis.



a)Main seismic load ; P_{EM} b)Secondary seismic loads, P_{ES}

Figure 2. *Main and Secondary seismic loads*



a) Repair limit level b) Ultimate limit level

Figure 3. *Comparison of axial forces between pushover analysis and time history analysis*

5.3 Equivalent static seismic loads determined based on integrated judgments

Several structures were investigated in the studies [7, 8] and reported not only to grasp the earthquake responses of metal roof spatial structures but also to evaluate their equivalent static seismic loads, and the results are explained in detail in the books. Generally, in their studies, first, a set of time history analysis were performed and followed by an endeavor judging globally responses to find seismic force distributions over the surface of each structure as explained in Section 5.1. Recently, the static seismic loads on typical shaped metal spatial structure [42, 58, 63-67] have been proposed based on such judgments of the results given by time history response analysis or modal analysis.

(a) Arches and column supported arches

An arch or a column supported arch has been often adopted as one of fundamental structural elements of roof structures. An elastic response study [63] of a simple arch supported at its both ends under horizontal earthquakes presents the equivalent static seismic loads, interpreted as the horizontal and vertical distributions for loads, depending on various open angles. The span is rather small as 15meters. The results may be applied for design use. Also, an elastic response study of an arch supported by columns at both ends [64] provides a static seismic force, which is expressed in terms of several design parameters such as a natural period, rise-to-span ratio, and column height. The results are expressed in a non-dimensional form. A gable type truss structure supported by columns at both ends [65] was studied, and the static seismic loads have been evaluated in an almost same procedure as the study [64] using a first natural period and its total mass ratio for the two dominant modes.

(b) Cylindrical steel frame for membrane roofs supported by substructure of rectangular plan

The elasto-plastic behavior for a cylindrical steel frame for membrane roofs supported by a substructure of a rectangular plan was studied in the references [62, 66]. The study [66] presents a numerical scheme for evaluating static seismic loads considering the interaction between the super- and substructures, followed by comparison with the results based on CQC method. The study [62] has proposed a scheme to evaluate a set of equivalent static seismic loads considering the elasto-plastic behavior of the substructure, and the seismic loads proposed were applied to a pushover analysis for performance based design, followed by a discussion on the possibility and efficiency of adaptive seismic loads changing dependent to deformations of structures.

(c) Cylindrical lattice roofs supported by substructures

A single layer latticed cylindrical roof [67] was studied under horizontal earthquake motions to obtain the relationship between total strain energy and various response quantities through linear elastic response analysis. Based on the results a set of static seismic loads and its calculation scheme have been proposed with a comparison between the static ones and time history analysis. According to the comparison, the peak responses of stresses are approximated using the accelerations at the time when the total strain energy reaches at peak values. For this kind of elastic structures of shallow rise roofs supported by substructures, the studies [58, 42] also explain the vibration mechanism and present a practical and approximate design formula of equivalent static seismic loads covering widely ranging structural parameters for design use. They are considered a kind of extension to a steel frame by adopting the concept of the study [66] for a membrane roof with a substructure on a rectangular plan.

(d) Single layer lattice dome supported by substructures

A medium size elastic dome with 60 meter span [42, 56], supported by a set of elastic flexible columns, was studied to obtain equivalent seismic loads. The studies considered several parameters such as a half open angle ranging 20 to 40 degrees, several depth-to-span ratios, and the variation of rigidity of substructure. The results point out a possibility that many modes are parallelly stimulated in case of relatively a small depth-to-span ratio, and an approximate but efficient estimation procedure of equivalent static seismic loads have been proposed for such domes. For a dome with a depth-to-span ratio being larger than 1/50, being considered relatively thick as a lattice dome, the maximum acceleration distribution in the horizontal and vertical directions, A_H and A_V, have been expressed by simple amplification factors, F_H and F_V. F_H and F_V are expressed in terms of the following functions, using the coordinates x and y in the roof. The equations for the seismic static loads are given as follows,

$$A_H(x,y) = A_{eq}\left\{1+(F_H-1)\cos\frac{\pi\sqrt{x^2+y^2}}{L}\right\} \qquad (1.1)$$

$$A_V(x,y) = A_{eq}F_V\frac{x}{\sqrt{x^2+y^2}}\sin\frac{\pi\sqrt{x^2+y^2}}{L} \qquad (1.2)$$

$$F_H = \begin{cases} 3 & (0<R_T\le 5/36) \\ \sqrt{5/4R_T} & (5/36<R_T\le 5/4) \\ 1 & (5/4<R_T) \end{cases} \qquad (1.3)$$

$$F_V = \begin{cases} 3C_V\theta & (0<R_T\le 5/16) \\ \left(\sqrt{5/R_T}-1\right)C_V\theta & (5/16<R_T\le 5) \\ 0 & (5<R_T) \end{cases} \qquad (1.4)$$

in which the maximum acceleration of a SDOF model obtained from response spectrum is defined as A_{eq} using θ of a half open angle of dome. The comparison between above factors and CQC results are shown in Figure 4. The proposed method is confirmed fine through the comparison. The similar statically equivalent seismic forces are provided also for cylindrical shells in the study [42], including the explanation of theoretical background.

For a high-rise dome, the equivalent seismic load [10, 68] was also studied. In the reference [68], a half-open angle θ of the dome was varied from 30° to 90° with a constant span of 60m. In the case of a high-rise dome, seismic static loads are expressed in terms of several simple amplification factors almost similarly to those of the studies [42], and their validities are discussed by comparing the equivalent seismic loads with those by response spectrum analyses and CQC method.

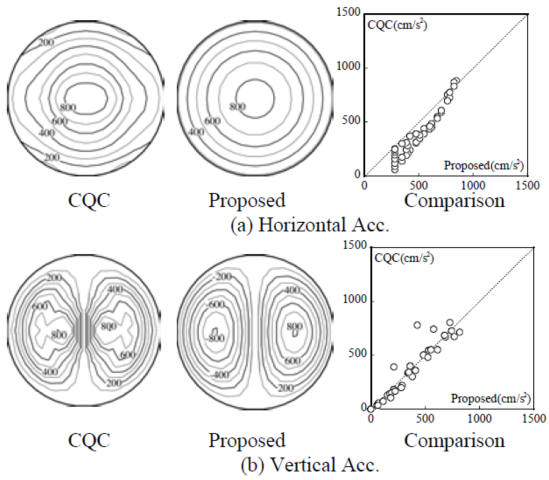


Figure.4. Acceleration Distributions in Dome

(e) Dome roof with seismic isolation system

The studies [18-24] have confirmed that a seismic isolation system effectively reduces not only the horizontal and but also anti-symmetrical vertical acceleration responses caused by horizontal seismic ground motions. The isolation system is also proved effective against both horizontal and vertical seismic ground motions. Although a time history response analysis has been used in actual design practice of spatial structures with isolation system installed, static seismic loads of domes have been also studied considering the effects of substructure and seismic base isolation system, since too large amount of outputs from time history analysis are likely to hide a fundamental response characteristics and lead wrong judgments. In the study [69], a method to determine the seismic force for the medium span latticed domes with isolation has been proposed in terms of amplification factors. In case that a substructure is light and stiff, the amplification factors, F_{h} and F_{v} in Eq.(1), are estimated by a SDOF model including the effect of the substructure. In case that the substructure is much heavier than the roof and its natural period of the substructure approaches near to that of the seismic isolation system, the maximum response of the roof can be evaluated by combining the equations of amplification factors and a predictive method for a mid-story seismic isolation system using double-DOF model.

6. EVALUATION OF FAILURE AND SEISMIC RISK ANALYSIS

Recently, researches have been performed aiming to find the failure mechanism how roof spatial structures collapse under severe earthquake motions. The studies [25, 70] focused on several domes being rigidly connected at nodes, and they investigated the collapse mechanism of the lattice domes and their failure accelerations under severe earthquake motions using detailed nonlinear analysis.

The study [70] of a dome of 40m span with a direct support reports an important fact that dynamic strength failure was not found in ordinary cases. Studies for double layer lattice domes [41, 71] were performed considering the effects of vertical earthquake motions, and they estimated collapse accelerations and revealed a high resistant capacity against vertical earthquake motions. In the reference [71], the input maximum accelerations and input strain energy of double layer lattice domes at collapse were numerically investigated. It says that the index of earthquake input energy might be more effective than that of the maximum input acceleration for the prediction of the collapse level under seismic loads. The earthquake input energy for dynamic collapse might be predicted by using the pseudo velocity response spectrum and information from the structural effective mass ratios.

Studies [70, 72, 73] on the damage evaluation of spatial structures have been recently performed as an extension of the study which analyzed the collapse acceleration and earthquake resistant performance. They discussed about the damage evaluation criteria for the structural components which constitute a spatial structure, and the damage evaluation approach has been proposed. In the reference [72], discussions have been presented with respect to a single layer lattice dome on the seismic fragility curve; a relation between input seismic intensity and failure probability was studied based on time history elasto-plasticity seismic response analysis.

In the recent earthquakes in Japan [12-15], the damages such as the falling-down of ceiling materials, finishing materials and lighting equipments have attracted greater attention as similarly to or more than structural damages to spatial structures. It is because such damage to nonstructural elements means a cease of the functions as buildings. Consequently, it is urgently necessary to investigate and propose an efficient evaluation method for determining the seismic performance in consideration of the damages to these non-structural components. Experimental and numerical studies [74, 75] on the response of ceilings within large roofs are urgent and important in order to evaluate the seismic loss more correctly.

A Seismic Risk Analysis (SRA) is adopted for evaluating the damage of spatial structures including the damage to non-structural elements [76-79]. SRA is a tool to quantify the seismic risk of an individual facility, with aims at providing information for decision making on risk mitigations. In the studies [76, 77], where a single layer lattice dome is divided into structural and non-structural elements, a seismic fragility has been evaluated based on time history analysis. Consequent to the results, the studies reported how much the damage of the upper dome structure could be effectively reduced by such energy absorption devices installed in the substructure. In the studies to calculate the failure probability of a structure including nonlinearity, an approach such as Monte Carlo simulation was applied with a help of parallel computing system [77], since a vast amount of response simulation for damage assessment is required in case of Monte Carlo method.

7 . CONCLUSIONS

The present paper is a brief state-of-the-art review for earthquake response analysis methods and statically equivalent seismic loads for metal spatial structures, by quoting investigations mainly from IASS symposia and related journals.

First, dynamic response characteristics of metal spatial structures have been briefly investigated including an explanation how such structures have been damaged due to or have survived severe earthquakes. Second, analytical methods for evaluating earthquake responses and statically equivalent seismic loads ever proposed for metal spatial structures have been reviewed. Consequent to several studies, examples of estimated seismic loads were presented which will be applied in practical design. Finally, necessity of seismic risk analysis was briefly discussed by referring to several studies from a view point of how damage or loss caused by earthquakes should be evaluated including not only structural member but non-structural elements.

ACKNOWLEDGEMENTS

The present study was performed as a part of activities of Sub WG for Dynamic Aspects of Metal Spatial Structures, WG No.8, and the authors would like to express their sincere appreciation to all of the colleagues assisting the present woks as well as to reviewers who kindly reviewed the present paper with keen critics and to IASS Journal who provides invaluable spaces. As described at the beginning, WG8 continues to introduce state-of-the-art views for design earthquake motions, earthquake response analysis methods, equivalent seismic loads, application of energy absorbing dampers, and evaluation of structural performance and other related researches. Finally, the authors would be grateful if the present paper is effectively utilized by IASS members and engineers involved in Shell and Spatial Structures.

REFERENCES

[1] ***S. Kato, T. Takeuchi, S.D.Xue, S. Nakazawa, I.Tatemichi, M.Fujimoto, F.Fan, T. Ogawa, Zhi-hua Chen, T.Kumagai*** : State-of-Art Report on Seismic Response Estimation of Metal Spatial Structures under Earthquake Motions, *Proceedings of the IASS-APCS 2006*, China, Beijing, 2006, DR10.

[2] ***S.D.Xue, S.Kato, T.Takeuchi, S. Nakazawa, T.Ogawa, P.Zhuang*** : A Review on Methods of Seismic Response Analysis of Metal Spatial Structures, *Proceedings of the IASS-APCS 2006*, China, Beijing, 2006, DR34.

[3] ***T. Takeuchi, S. D. Xue, S. Kato, T. Ogawa, M. Fujimoto, S. Nakazawa***: Recent Developments in Passive Control Technologies for Metal Spatial Structures, *Proceedings of the IASS-APCS 2006*, China, Beijing, 2006, DR18.

[4] ***T. Takeuchi, T. Ogawa, T. Kumagai***: State-of-Arts Views on Response Control Technologies on Metal Space Structures, *Proceedings of the IASS 2009*, Valencia, Spain, 2009, 104-105.

[5] ***S. D. Xue, X. Y. Li, T. Takeuchi, S. Kato***: Review and New Development of Seismic Isolation Technology for Spatial Structures, *Extended Abstracts of IASS2010*, China, Shanghai, 2010, pp.74-75.

[6] ***S. Nakazawa, S. Kato, T. Takeuchi, S. D. Xue*** : State-of-Art Views on Seismic Response Evaluation Methods for Metal Spatial Structures, *Extended Abstracts of IASS2010*, China, Shanghai, 2010, 76-77

[7] Spatial Structures - Seismic Design and Realization in Japan, *published by Architectural Institute of Japan*, 2001 (in Japanese)

[8] Dynamic Behavior and Seismic Design of Spatial Structures, *published by Architectural Institute of Japan*, 2006 (in Japanese)

[9] ***S. Kato, K. Ishikawa, Y. Yokoo*** : Materially Nonlinear Dynamic Stability of Trussed Beams of Long Span due to Vertical

Earthquake Motions, *Proceedings of the 4th International Conference on Applied Numerical Modeling*, Taiwan, 1984, 215-219.

[10] ***S. Kato, T. Ueki, Y. Mukaiyama*** : Study of Dynamic Collapse of Single Layer Reticular Domes Subjected to Earthquake Motions and Estimation of Statically Equivalent Seismic Force, *International Journal of Space Structures*, Vol.12, Nos.3&4, 1997, 191-203.

[11] ***T. Ogawa, T. Takeuchi, M. Nakagawa, T. Kumagai*** : Seismic response analysis of single layer lattice domes, *Proceedings of the IASS-APCS 2003*, Taipei, Taiwan, 2003, 110-111.

[12] ***S. Kato, K. Kawaguchi, T. Saka***: Preliminary Report on Hanshin Earthquake, *Proceedings of the IASS 1995*, Vol.2, 1995, 1059-1066.

[13] ***K. Kawaguchi and Y. Suzuki*** : Damage Investigations of Public Halls in Nagaoka City After Nigata-Chuetsu Earthquake 2004 in Japan, *Proceedings of the IASS 2005*, Vol.I, 2005, 421-428.

[14] Report on the Hanshin-Awaji Earthquake Disaster, Building Series Volume 3, Architectural Institute of Japan, 1997

[15] Report on the Damage Investigation of the October 23,2004 Mid Niigata Prefecture Earthquake, Architectural Institute of Japan, 2006

[16] ***Y. Feng, Y. Liu, X. Xia***: Grid Structures in Wenchun Earthquake, *Extended Abstracts of IASS2009*, Valencia, Spain, 2009, 106-107.

[17] Experience the Wencuan Earthquake – Structural Engineers' Point and View, China Southwest Architecture Design & Research Institute, Beijing Architecture Engineering Publication, 2009

[18] ***M. Uchikoshi, S. Kato, S. Nakazawa, T. Mukaiyama***: How to Realize a Super Large Dome under Severest Earthquake ? A Dome with Seismic Isolation System, *Proceeding of IASS 2001*, TP115.

[19] ***M. Kawaguchi and I. Tatemichi***: Seismic Isolation Systems and Their Application in Space Structures, *Proceedings of the IASS 2000*, 2000, 217-228.

[20] ***Y. Hitomi, K. Osawa, S. Nakagawa, M Saitoh*** : Structural Design of Yamaguchi Dome, *Proceedings of the IASS 2001*, TP155, 2001.

[21] ***K. Kaneda, M. Saitoh***: Endeavors to Control the Vibration of Long Span Structures, *Proceedings of the IASS 2001*, TP116, 2001.

[22] ***K. Shingu, T. Niki***: A Study on Base Isolated Shell, *Proceedings of the IASS 2001*, Nagoya, TP117, 2001

[23] ***Z. Cao, S. D. Xue and Y. G. Zhang***: Analytical Model and Vibration Control For Lattice Shells, *Proceedings of the IASS 2004*, 2004, TP037.

[24] ***S. D. Xue, P. Zhuang, B. S. Li*** : Seismic Isolation of Lattice Shells Using a New Type of SMA-Rubber Bearings, *Proceedings of the IASS 2005*, 2005, 353-358.

[25] ***S. Kato, S. Nakazawa, T. Minegishi and Y. Niho***: Dynamic Collapse Mechanism of Single Layer Reticular Domes with Braces Subjected to Severe Earthquakes Motions, *Proceedings of the IASS 2000*, 2000, 319-326.

[26] ***S. Kato and S. Nakazawa*** : Seismic Design Method to Reduce the Responses of Single Layer domes by Means of Yielding of Substructure under Severe Earthquake Motions, *Proceedings of the IASS 2001*, 2001, TP077.

[27] ***S. Kato, S. Nakazawa, F. Matsushita, T. Ohya, T. Okamoto*** : A New System of Intermediate Isolation for Space Structures Against Earthquakes, *Proceedings of the 5th International Conference on Space Structures*, University of Surrey, Guildford, UK, 2002, 1053-1062.

[28] ***S. Kato, Y. B. Kim and S. Nakazawa***: Simulation System of Cyclic Behavior of Steel Hysteretic Devices and Study on Efficiency of the Devices Installed Into Space Structures for Reducing Earthquake Responses, *Proceedings of the IASS 2004*, TP053, 2004

[29] ***T. Takeuchi, K. Kaneda, M. Iwata, A. Wada, M. Saitoh*** : Vibration-Control Devices For Tension Structures Using Visco-elastic or Viscous Material with Spring, *Proceedings of the IASS 2001*, TP121, 2001.

[30] ***K. Kasai, S. Motoyui, Y. Ooki*** : Viscoelastic Damper Modeling and its Application to Dynamic Analysis of Viscoelastically Dampered Space Frames, *Proceedings of the IASS 2001*, TP119

[31] ***F.Fan, S.Z.Shen, G.A.R.Parke*** : Theoretical and Experimental Study of Vibration Reduction in Braced Domes Using a Viscous Damper System, *International Journal of Space Structures*, Vol.19, No.4, 2004, 195-202.

[32] ***G.C. Giuliani*** : Overview on the Dynamic Control of Structures, *Proceedings of the* IASS 2002, 2002, 561-567.

[33] ***G.C. Giuliani*** : Up To Date Dynamic Control of Structures, *Proceedings of the* IASS 2004, IL06, 2004.

[34] Technical specification for latticed shells JGJ 61-2003, China Building Industry Press, 2003

[35] Recent Spatial Structures in Japan, *IASS Journal*, Vol.42, n.2, 2001

[36] Recent Spatial Structures in China, *IASS Journal*, Vol.47, n.2, 2006

[37] Ministry of Land, Infrastructure and Transport, Notification, No.1457-2000, Technical Standard for Structural Calculation of Response and Limit Strength of Building, 2000 (in Japanese).

[38] Recommendations for Loads on Buildings, published from Architectural Institute of Japan (AIJ), 2004 (in Japanese).

[39] ***M. Midorikawa*** : Performace-Based Seismic Design Provisions for Buildings in Japan, *Proceedings of the IASS 2005*, Vol.I, 2005, 307-316.

[40] ***Y. Kitagawa, I. Okawa, T. Kashima*** : A Technique for Evaluation of Design Earthquake Ground Motion, Kenchiku Kenkyu Shiryo, published by Building research Institute, Ministry of Construction in Japan, No.83, 1994.11.

[41] ***K. Ishikawa, S. Kato***: Elastic-plastic Dynamic Buckling Analysis of Reticular Domes Subjected to Earthquake Motion, *International Journal of Space Structures*, Vol.12, Nos.3&4, 1997, 205-215.

[42] ***T. Takeuchi, T. Ogawa, T. Kumagai*** : Seismic Response Evaluation of Lattice Shell Roofs Using Amplification Factors, *Journal of the IASS*, Vol.48, No.3, 2007

[43] ***S. Kato, S. Nakazawa and K. Saito*** : Two-Mode Based Estimation of Equivalent Seismic Loads and Static Estimation of Dynamic Response of Reticular Domes Supported by Ductile Substructures, *Journal of the IASS*, Vol.47, 2006, 35-52.

[44] ***L. Su, S. L. Dong, S. Kato***: A new Average Response Spectrum Method for Linear Response Analysis of Structures to Spatial Earthquake Ground Motions, *Engineering Structures*, Vol.28, 2006, 1835-1842.

[45] ***S. Kato, S. Nakazawa, Liang Su***: Effects of Passage and local Site on Seismic Response of a Single Layer Reticular Dome Structure, *Steel Construction Engineering*, Vol.10, No.37, 2003, 91-106.

[46] ***L. Su, S. L. Dong, S. Kato***: Seismic Design for Steel Trussed Arch to Multi-Support Excitations, Engineering Structures, Vol.63, 2007, 725-734.

[47] ***Y. Shi, Y. Jiang, Y. Wang***: Time-history Analysis of Seismic Response of Heifei Xinqiao Airport Terminal Subjected to Non-uniform Ground Motions, *Extended Abstracts of IASS2010*, China, Shanghai, 2010, 369-370.

[48] ***D. Zhou, Y. Feng, X. Jian*** : Time-history Analysis of Terminal 2 of the Chengdu Shuangliu Airport under Multi-support and Mult-dimension Seismic Excitation, *Extended Abstracts of IASS2010*, China, Shanghai, pp.375-376, 2010

[49] ***S. Kato, S. Nakazawa, M. Uchikoshi*** : How Does the Assumption of Damping Matrix Influence on the Earthquake Response of Large Reticulated Domes with Seismic Isolation System ?, *Proceedings of the IASS 1999 Symposium*, Madrid, Spain, 1999, E2.31-2.40.

[50] ***D. Yang, Y. Zhang, J. Wu***: Computation of Reyleigh Damping Coefficients in seismic Time-History Analysis of spatial Structures, *Journal of IASS*, Vol.51, No2 June n.164, 2010, 125-135.

[51] ***I. Tatemichi*** : A Study on the Damping of Vibrations in Space Structures, *Proceedings of the IASS 2001*, TP074, 2001

[52] Damping and Response Control of Shell and Spatial Structures, published by Architectural Institute of Japan, 2008. (in Japanese)

[53] ***O. Hosozawa, T. Mizutani*** : Structural Design of Simokita Dome, *Proceedings of the IASS 2005.*

[54] ***T. Takeuchi, Y. Tutsumi, T. Kumagai, T. Ogawa***: Seismic Retrofit of Steel-structure School Gymunasia with Energy Dissipation Braces, *Extended Abstracts of IASS2010*, China, Shanghai, 2010, 78-79.

[55] ***T. Kumagai, T. Takeuchi, T. Ogawa A. Nakama and E. Sato*** : Seismic Response Evaluation of Latticed Domes with Elasto-Plastic Substructures Using Amplification Factors, *Proceedings of the IASS 2005*, Vol. I, 2005, 383-390.

[56] ***T. Takeuchi, T. Ogawa, M. Nakagawa and T. Kumagai*** : Response Evaluation of Medium Span Lattice Domes with Substructures using Response Spectrum Analysis, *Proceedings of the IASS 2004*, 2004, TP076.

[57] ***T. Takeuchi, T. Ogawa, C. Yamagata and T. Kumagai***: Seismic Response Evaluation of Cylindrical Lattice Shell Roofs with Substructures Using Amplification Factor, *Proceedings of the IASS 2005*, Vol.I, 2005, 391-398.

[58] ***S. Kato, Y. Konishi, S. Nakazawa***: Pushover Analysis and Static Estimation of Seismic Response of Large Steel Space Structures, *Proceedings of the IASS-APCS 2003*, 2003, 54-55.

[59] ***S.D. Xue, Z. Cao and X.S. Wang:*** Random Vibration Study of Structures under Multi-Component Seismic Excitations, Advances in Structural Engineering, 2002, 5(3), 185-192.

[60] ***S.D Xue, X.S. Wang and Z. Cao:*** Multi-Dimensional Pseudo Excitation Method for Nonstationary Random Seismic Analysis of Spatial Lattice Shells, International Journal of Space Structures, 2004, 19(3), 129-136.

[61] ***S. Kato, S. Nakazawa, K. Saito***: Estimation of Static Seismic Loads for Latticed Domes Supported by Substructure Frames with Braces Deteriorated due to Buckling, *Journal of the IASS*, Vol.48, 2007, 71-86.

[62] ***S. Nakazawa, S. Kato, T. Yoshino and K. Oda*** : Study on Seismic Response Estimation Based on Pushover Analysis for Membrane Structures Supported by Substructure, *Proceedings of the* IASS 2005, Vol. I, 2005, 329-336.

[63] ***C. Hung, Y. Shinohara, M.Yamada***: A Study on the Static Seismic Force for the Design of the Arch, *Proceedings of IASS 2001*, 2001, TP080.

[64] ***S. Kato, S. Nakazawa, X.Gao*** : Elastic Responses and Equivalent Static Forces for Large Span Arches, *Proceedings of IASS 2002*, 2002, 524-529.

[65] ***S. Kato, S. Nakazawa, F. Atsumi*** : A Study on Elastic Seismic Response and Estimation of Static Seismic Load of the Gable Trussed Structures, *Steel Construction Engineering*, Vol.9, No.33, 2002, 2002, 65-80.

[66] ***J. Fujiwara, T. Takeuchi, K. Oda*** : Seismic Response Evaluation for Framed supported Membrane Roof Structure Using Equivalent Static Loads - An Example with a Single Layer Cylindrical Roof Structure -, *Research Report on Membrane Structures 2005*, No.19, 2005, 399-406.

[67] ***S. Yamada, Y. Matsumoto, E. Saito*** ; Seismic Response Behavior of Single Layer Latticed Cylinndrical Roofs and the Load Modeling for Seismic Design, *Proceedings of IASS 2005*, Vol.I, 2005, 399-406.

[68] ***T. Takeuchi, T. Kumagai, S. Okayama, T. Ogawa***: Seismic Response Evaluation of Low – to – High rise Lattice Domes, *Proceedings of APCS 2009*, Nagoya, Japan, 2009, 71-72.

[69] ***K. Takamatsu, T. Takeuchi, T. Kumagai, T. Ogawa*** : Response Evaluation of Seismically Isolated Lattice Domes using Amplification Factors, *Proceedings of IASS Symposium 2009*, Valencia, Spain, 2009, 120-121.

[70] ***Z. Xudong, F. Feng, S. Shizhao*** : Failure mechanism of single-layer reticulated domes subjected to earthquakes, *Journal of the IASS*, 2007, 48(2), 29-44.

[71] ***Y. Taniguchi, P. L. Gould, M. Kurano*** : Earthquake Input Energy at Dynamic Collapse for Double-Layer Cylindrical Lattice Roofs, *Journal of the IASS*, Vol. 49, No. 2, 2008.

[72] ***D. Yang, Y. Zhang, J. Wu***: Seismic Performance Assessment of Single Layer Latticed Domes Using IDA, *Proceedings of the APCS 2009*, Nagoya, 2009, APCS09-P0067.

[73] ***D. Yang, Y. Zhang, J. Wu, W. Liu***: A Method for the Damage Assessment of Single-layer Lattice Shells by Performing Static Stability Analysis Twice, *Extended Abstracts of IASS2010*, China, Shanghai, 2010, 291-293.

[74] ***K. Kawaguchi, T. Uchida, Y. Ogi, S. Ohya***, Experimental Study on Safety of Suspended Ceilings in Large Rooms, *Extended Abstracts of IASS2010*, China, Shanghai, 2010, 351-352.

[75] ***K. Ishikawa***: Effects of Resonance between Spatial Structures and Ceiling Systems on the seismic Response, *Proceedings of the IASS 2009*, Valencia, Spain, 2009, 108-109.

[76] ***S. Nakazawa, T. Shima, I. Tatemichi, S. Kato, K. Hirano***: Evaluation for Seismic Risk Based on Damage Ratio and Seismic Resistance of Spatial Structures, *Proceedings of the IASS-APCS2006*, China, Beijing, 2006, AO16.

[77] ***S. Nakazawa, S. Kato, R. Shibata*** : Seismic Risk Evaluation of Spatial Structures by using Grid Computing System, *Proceedings of IASS Symposium 2009*, Valencia, Spain, 2009, 366-377.

[78] ***S. Kato, S. Nakazawa*** : A Trial for Seismic Fragility Evaluation of a Large Lattice Dome Supported by Buckling Restrained Braces, *International Journal of Space Structures*, Vol.25, No.2, 2010, 125-134.

[79] ***S. Nakazawa, Y. Yagi, S. Kato***: Evaluation of Seismic Performance of Single Layer Lattice Dome supported by Ductile Braces, *Extended Abstracts of IASS2010*, China, Shanghai, 2010, 93-94.